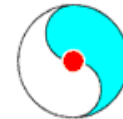


Hydrodynamic Model and Hard Probe

Tetsufumi Hirano



RIKEN BNL Research Center



Collaboration with Yasushi Nara (Arizona)

OUTLINE

- Introduction
- Hydro+jet model
- Back-to-back correlations
- R_{AA} for protons
- Jet quenching at $\eta \sim 2$
- Summary

References

T.H. and Y.Nara,
Phys.Rev. C**66**, 041901(2002);
Phys.Rev.Lett. **91**, 82301(2003);
nucl-th/0307015;
nucl-th/0307087.

JPS meeting @ Miyazaki, Sep.9, 2003

Introduction

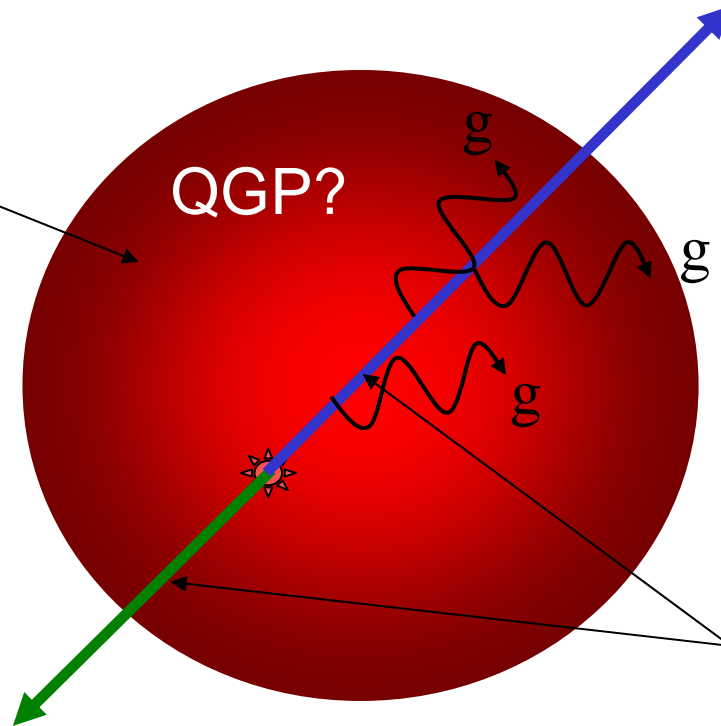
Hot and dense
matter produced in
heavy ion collisions



Not static,
but dynamic!



Need a *dynamic*
model



1. Jet quenching

Gyulassy, Plumer ('90)
Wang, Gyulassy ('92)
and a lot of work

correlate ?

2. Jet acoplanarity

(transverse momentum imbalance)

Bjorken ('82)

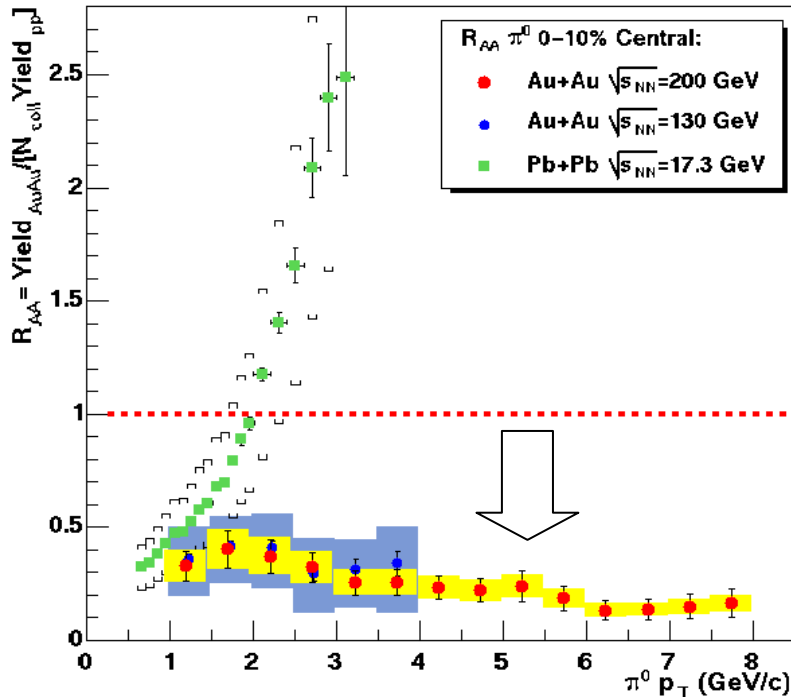
Appel ('86)

Blaizot, McLerran ('86)

Rammerstorfer, Heinz ('90)

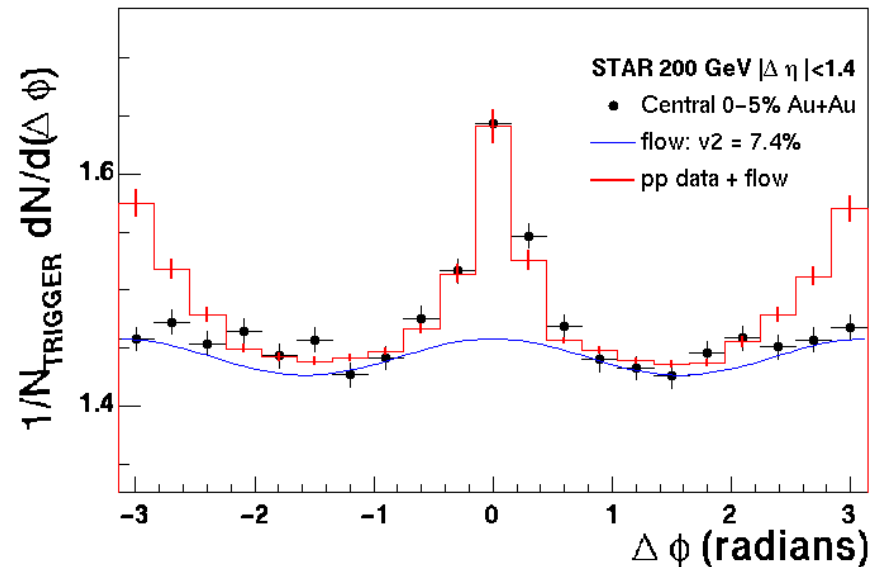
High p_T data at RHIC

$$R_{AA} = \frac{dN^{AA}/dp_T d\eta}{\langle N_{\text{coll}} \rangle dN^{pp}/dp_T d\eta}$$

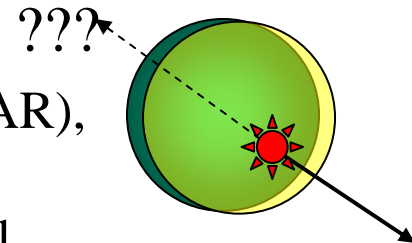


From D. d'Enterria(PHENIX),
talk at QM2002. See also,
S.S.Adler et al.(PHENIX),
PRL91,072301(2003).

$$\frac{1}{N_{\text{trigger}}} \frac{dN}{d\Delta\phi} = \frac{1}{N_{\text{trigger}}} \int d\Delta\eta \frac{dN}{d\Delta\phi d\Delta\eta}$$

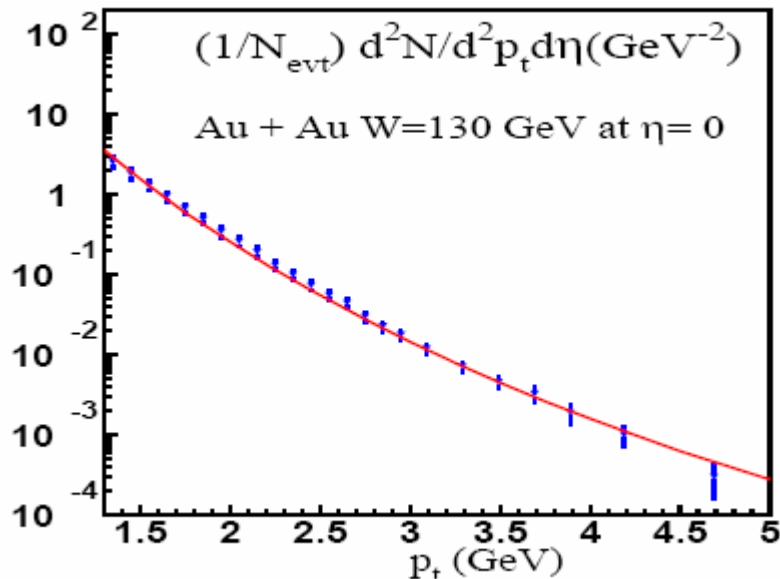


From D.Hardtke (STAR),
talk at QM2002.
See also, C.Adler et al.
(STAR), PRL90,082302(2003).



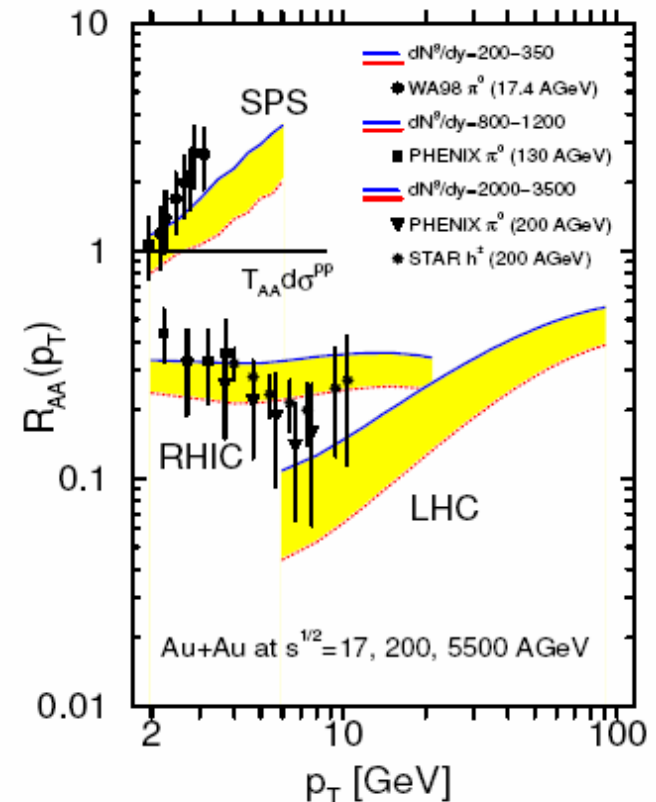
Initial or Final ?

D.Kharzeev *et al.*, Phys.Lett.B**561**, 93(2003).



- Parton saturation $\rightarrow N_{\text{part}}$ scaling
- $gg \rightarrow g$ (no b-to-b)

I.Vitev and M.Gyulassy,
Phys.Rev.Lett. **89**, 252301(2002)



- pQCD+Cronin+shadowing
+jet quenching+simple expansion

Our approach (“final effect”):
Dynamical simulation of both a QGP fluid and minijets

Model

- Jet quenching
- Jet acoplanarity

Interaction between **soft** and **hard**
is *important!*

Hydro + Jet model

Soft (hydrodynamics)

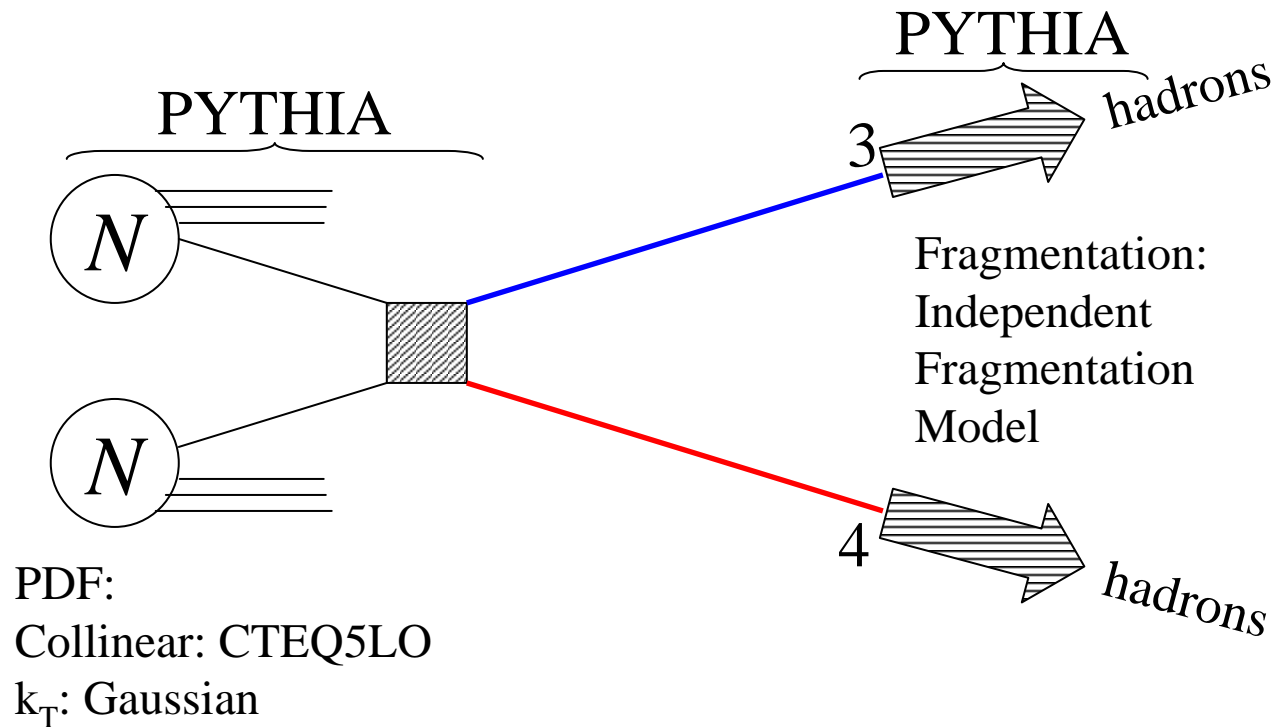
- Space-time evolution of matter
- Phase transition between QGP and hadrons
- Particle spectra in low p_T region

Hard (mini-jets)

- Production of (mini-)jets
- Propagation through fluid elements
- Fragmentation into hadrons

Interaction between fluids and mini-jets through parton energy loss

PYTHIA



pQCD LO:

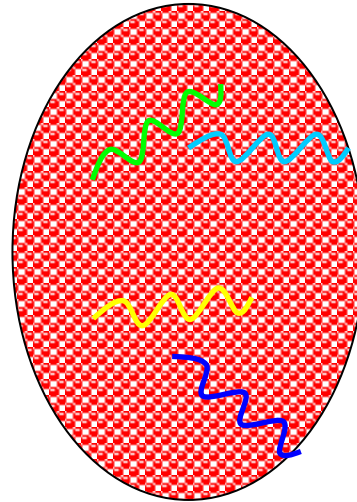
$$\begin{aligned}
 &q + q' \rightarrow q + q', q + \bar{q} \rightarrow q + \bar{q} \\
 &q + \bar{q} \rightarrow g + g, q + g \rightarrow q + g \\
 &g + g \rightarrow g + g, g + g \rightarrow q + \bar{q}
 \end{aligned}$$

$$\begin{aligned}
 E \frac{d\sigma_{\text{jet}}^{pp}}{d^3p} &= K \sum_{ab} \int g(k_{T,a}) d^2k_{T,a} g(k_{T,b}) d^2k_{T,b} \\
 &\times \int f_a(x_1, Q^2) dx_1 f_b(x_2, Q^2) dx_2 E \frac{d\sigma^{ab \rightarrow cd}}{d^3p}
 \end{aligned}$$

*Initial and final state radiation are included.

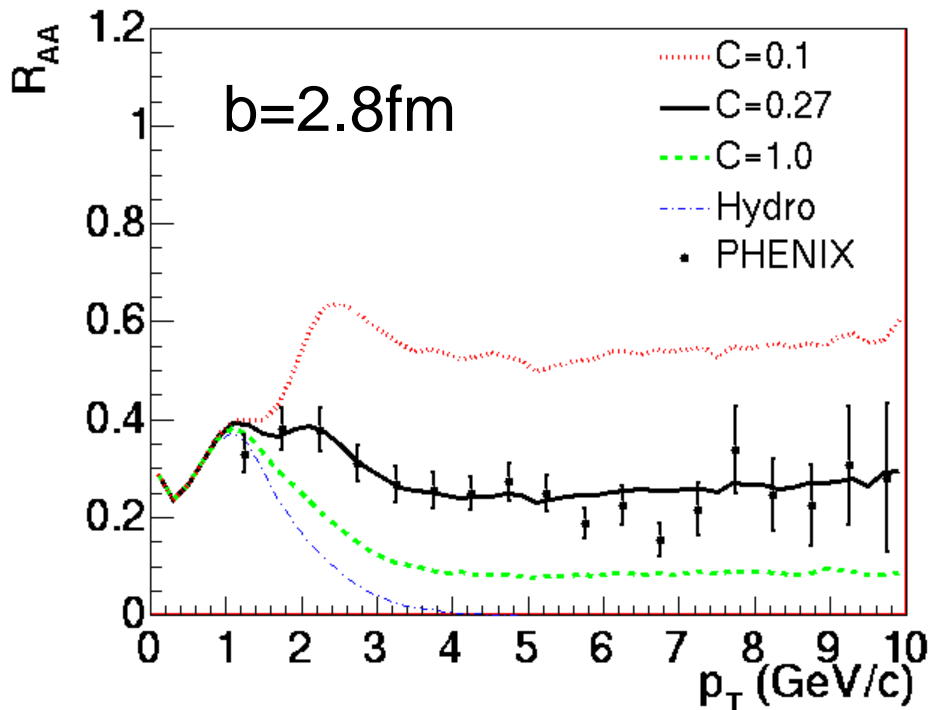
(+Hydro)

3D Hydro



Parton energy loss:
GLV 1st order formula

Suppression Factor for π^0



$$R_{AA} = \frac{dN^{AA}/dp_T d\eta}{\langle N_{\text{coll}} \rangle dN^{pp}/dp_T d\eta}$$

Data from S.S.Adler et al. (PHENIX),
PRL91,072301(2003).

Simplified GLV 1st order formula:

$$\Delta E = -C \int_{\tau_0}^{\infty} d\tau (\tau - \tau_0) \rho(\tau, \mathbf{x}(\tau)) \ln \left(\frac{2p_0^\mu u_\mu}{\mu^2 L} \right)$$

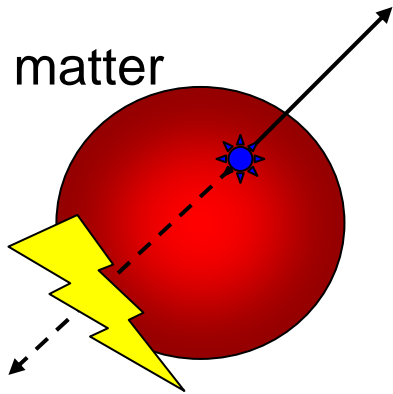
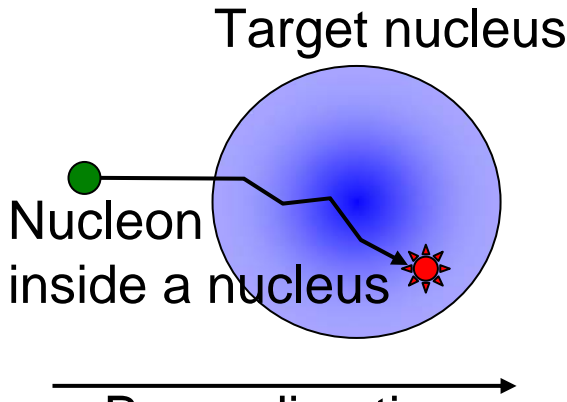
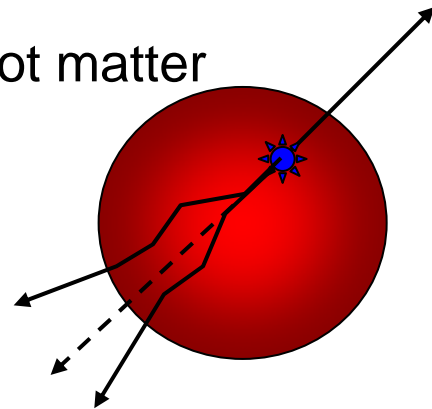
M.Gyulassy *et al.*, NPB**594**, 371 (2000).

GLV formula with
 $C=0.27$ quantitatively
reproduces the data



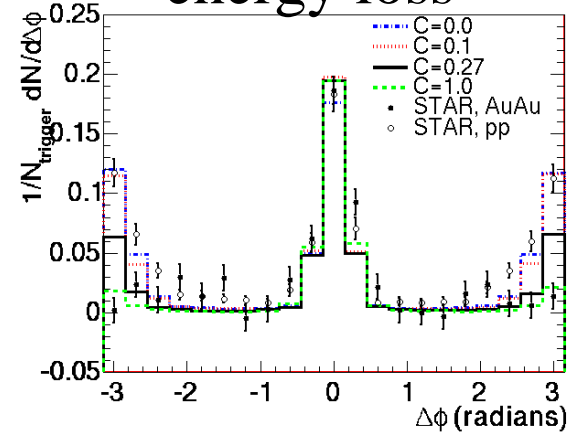
Our starting point of
the following discussion

Three Possible Effects on Back-to-back Correlations

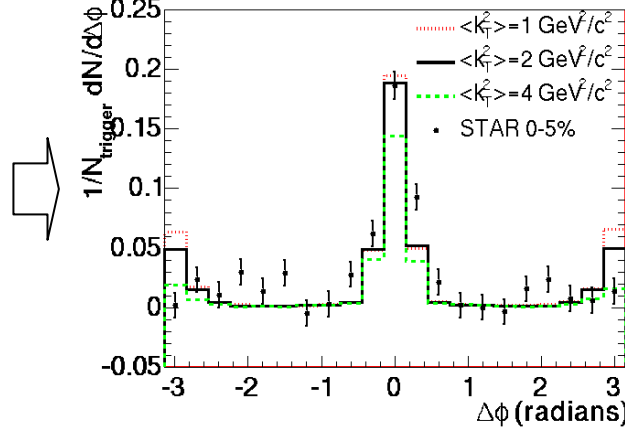
1. Energy loss of jets	2. Primordial k_T of initial partons	3. Broadening of jets
Final state	Initial state	Final state
<p>Hot matter</p>  <p>Absorption</p>	<p>Target nucleus</p>  <p>Nucleon inside a nucleus</p> <p>Beam direction</p> <p>“Cronin effect”</p>	<p>Hot matter</p>  <p>Random walk behavior</p>

Disappearance of B-to-B

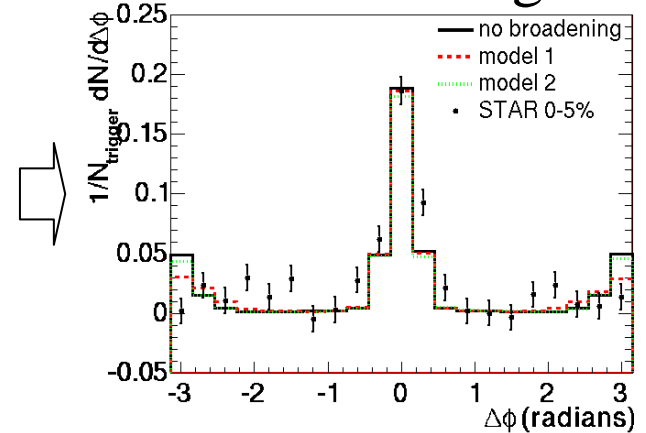
energy loss



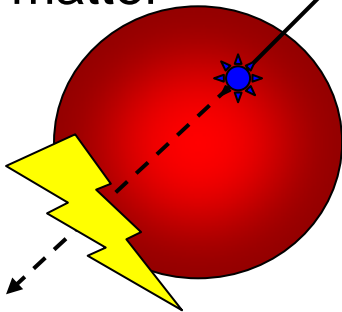
+Cronin effect



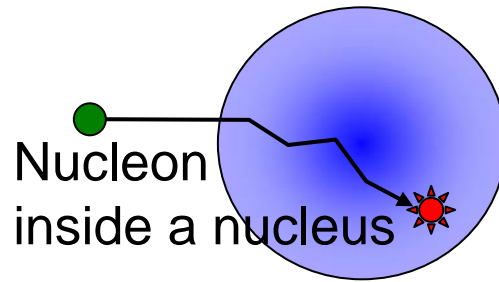
+broadening



Hot matter



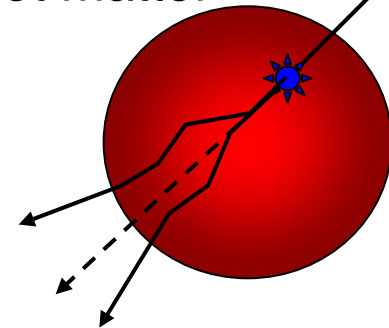
Target nucleus



Nucleon
inside a nucleus

Beam direction

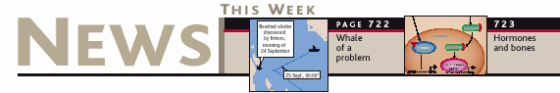
Hot matter



Energy loss is dominant, but insufficient.

Are Protons and Anti-Protons Suppressed ?

C.Seife, Science 298, 718 (2002)



HIGH-ENERGY PHYSICS

Wayward Particles Collide With Physicists' Expectations

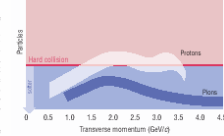
EAST LANSING, MICHIGAN—Physicists' quest for a new state of matter has taken a bewildering turn. At a meeting here last week, researchers from the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory in Upton, New York, announced results that, so far, nobody can explain. By slamming gold atoms together at nearly the speed of light, the physicists hoped to make gold nuclei melt into a novel phase of matter called a quark-gluon plasma. But although the experiment produced encouraging evidence that they had succeeded, it also left them struggling to account for the behavior of the particles that shoot away from the tremendously energetic smashups.

The more I think about it, the more I think it's not completely wacky," William Zajc of Columbia University, spokesperson for one of the four particle detectors at RHIC, said privately at the conference. Zajc ruminated for a few moments and then corrected himself: "Well, it is completely wacky," he said. "We don't get it. I really don't know—on a fundamental level."

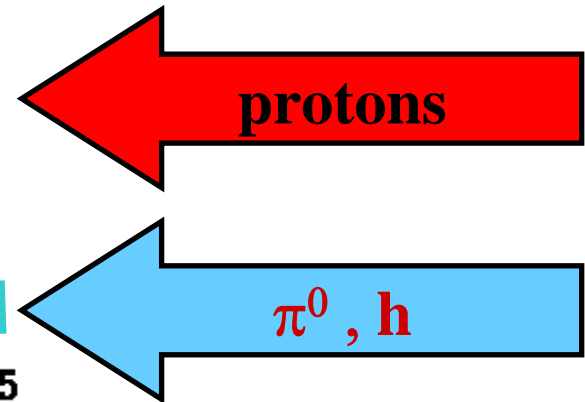
The confusion comes from PHENIX, one of the four detectors, which probed the differences between "hard" and "soft" nuclear collisions. Nuclear collisions of protons and neutrons, and at low energies, they behave

rather than merely ricocheting off the components of the nucleus. This tidy picture has just become considerably messier. With the higher energies and better statistics of RHIC's second year of running, physicists could classify the particles zooming away from the collisions. What they saw was a shock. Measurements at PHENIX indicate that some of the particles flying away from the smashups are moving more slowly than normal, as one would expect in a soft collision, but others are coming out of the woods as if from a hard collision (see figure). Scientists know of no plausible mechanism for this discrepancy. "It's a true puzzle," says Zajc.

Part of the problem is that most of the particles PHENIX detects are born after the collision—sprung from more or less identical quarks and gluons (collectively dubbed "partons") that scatter off one another at the moment the two atoms crash together. The flying partons only then recombine into two-quark or three-quark ensembles ("hadrons," such as protons and neutrons). Because identical partons are doing the scattering, the hadrons they produce should all look as if they were born in the same sort of collision, soft or hard. But that isn't what PHENIX sees, says Julia Velkovska, a Brookhaven physicist who is also associated with the PHENIX experiment. Pions, two-quark ensembles made of up and down quarks and antiquarks (and a handful of gluons) bound in an uneasy package, "behave more or less exactly like predicted" for a particle traveling through a sticky medium like a quark-gluon plasma, she says, whereas pro-

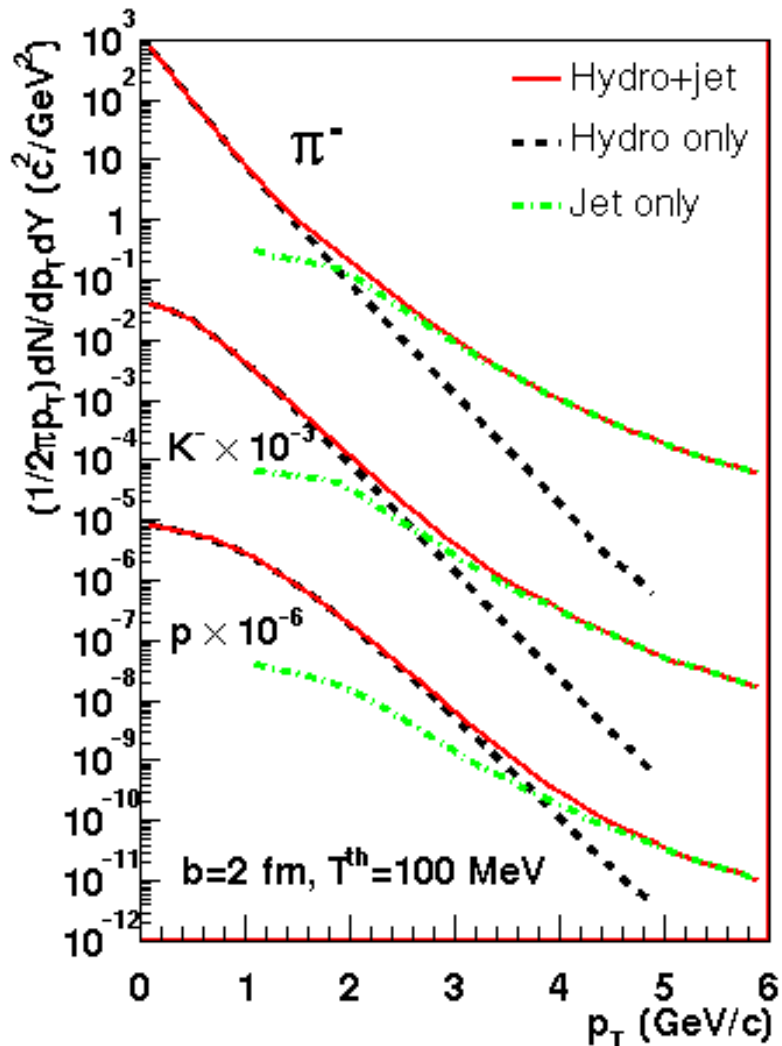


Hard riddle. At the Relativistic Heavy Ion Collider (top), protons and pions born from the same explosions inescapably show earmarks of different origins.



J.Velkovska, talk at DNP;
PHENIX, nucl-ex/0305036.

p_T Spectra for Identified Hadrons

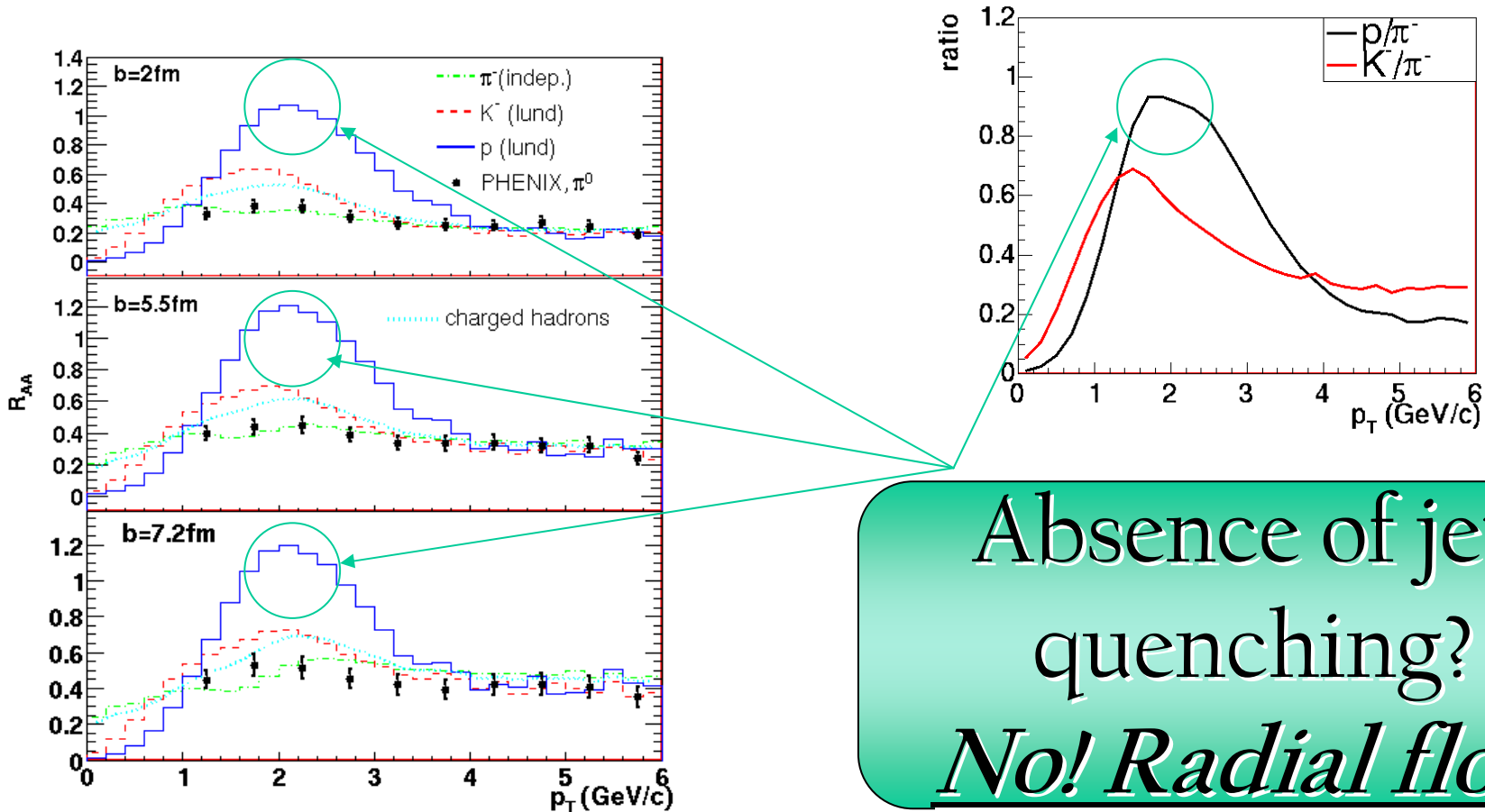


$p_{T,\text{cross}}$ depends on particle species!

$p_{T,\text{cross}} \sim 1.8 \text{ GeV}/c$ for π
 $2.7 \text{ GeV}/c$ for K
 $3.7 \text{ GeV}/c$ for p

c.f.) $p_{T,\text{cross}} \sim$ inflection point for kaons and protons

R_{AA} and Ratio for Identified Hadrons



Absence of jet
quenching?
No! Radial flow

n.b.) Similar mechanism for crossing v_2

Jet Quenching at Off-Midrapidity

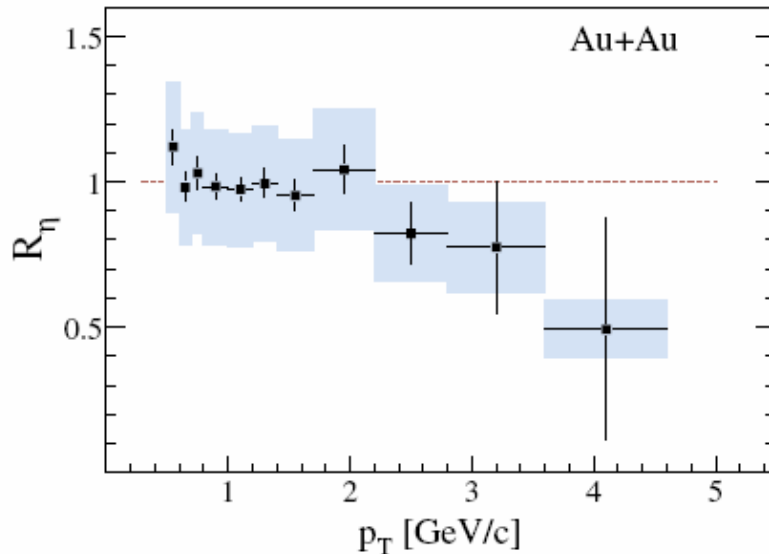


FIG. 3 (color online). Ratio R_η of R_{cp} distributions at $\eta = 2.2$ and $\eta = 0$. Statistical errors are indicated by the bars, while systematic errors are shown by the grey bands.

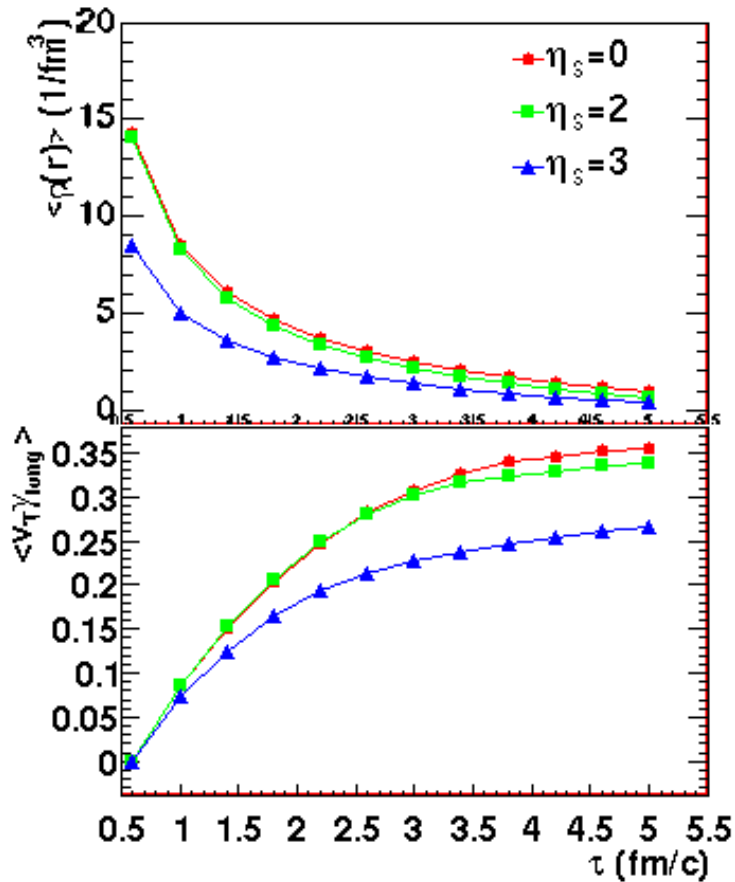
072305-3

$$R_\eta = \frac{R_{CP}(\eta = 2.2)}{R_{CP}(\eta = 0)}$$

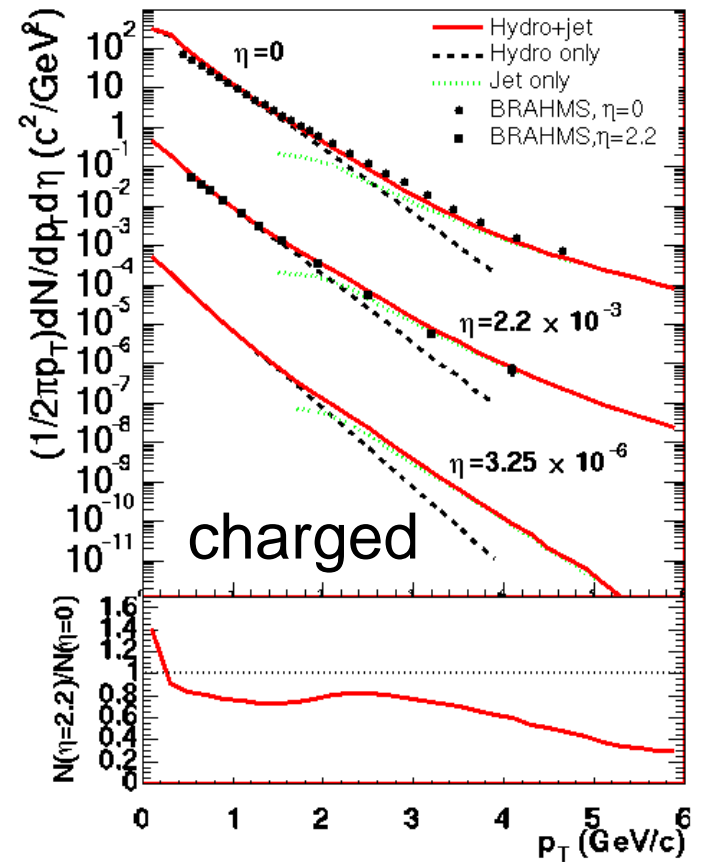
$$R_{CP} = \frac{\langle N_{\text{coll}}(P) \rangle}{\langle N_{\text{coll}}(C) \rangle} \times \frac{(\text{yield at Central})}{(\text{yield at Peripheral})}$$

BRAHMS, PRL91,072305(2003)

Hydro+Jet at Off-Midrapidity

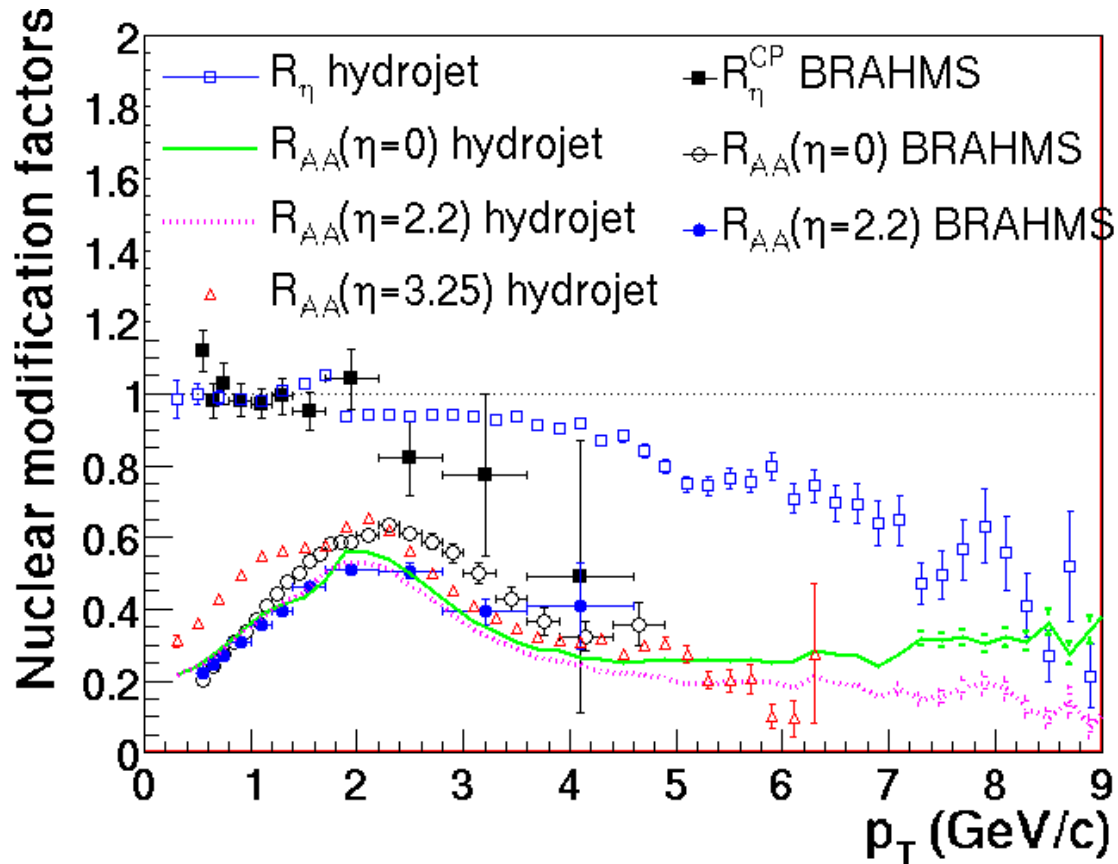


Dynamical effects should be identical between $\eta=0$ and 2.



Steeper pQCD component in forward rapidity.

Hydro+Jet at Off-Midrapidity (*cond.*)



Jet quenching
 → Shift of a spectrum
 Modification factor
 → Ratio at some p_T

Indication of dense
 partonic matter in
 forward rapidity
 regions ($\eta \sim 2$)

Summary

QGP in Au+Au collisions at RHIC ?

→ Final state effects are consistent with intermediate ~ high p_T data (R_{AA} , b-to-b, ...).

→ Strongly encouraged by recent $d+Au$ data.

- Dynamical model (hydro+jet) for heavy-ion physics

- Dominant effect of back-to-back correlations

→ Parton energy loss

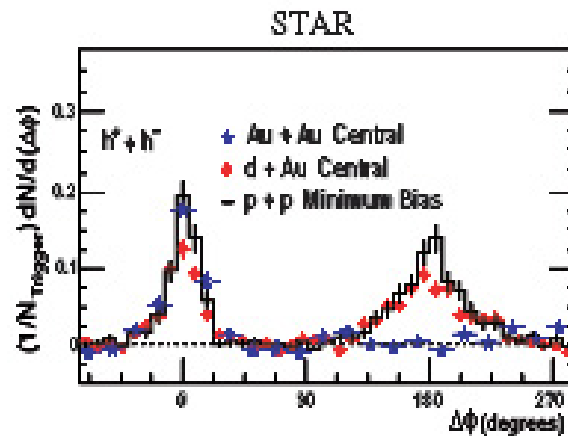
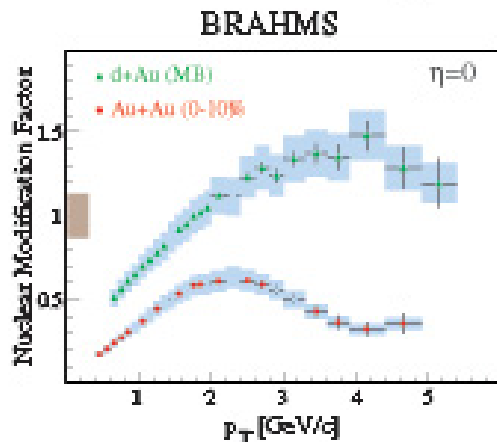
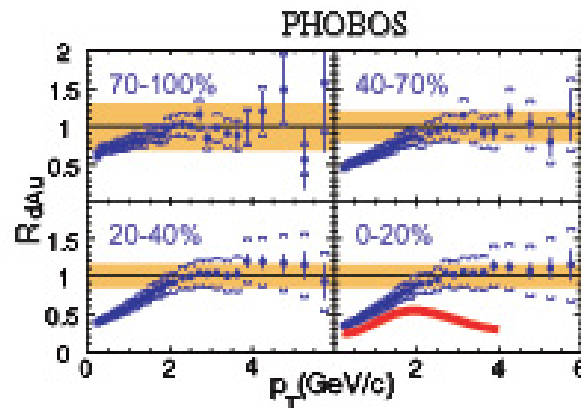
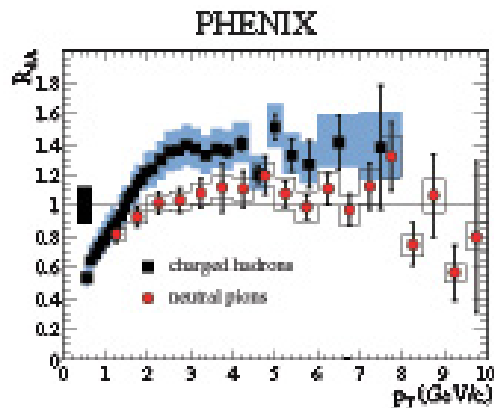
- Hadron species dependent transverse dynamics

→ **Interplay** between radial flow and jet quenching

- How large dense matter in longitudinal direction?

← Jet quenching in forward rapidity region ($\eta \sim 2$)

Recent Data in $d+Au$ Collisions



PRL91,(03)072302;
072303;
072304;
072305.

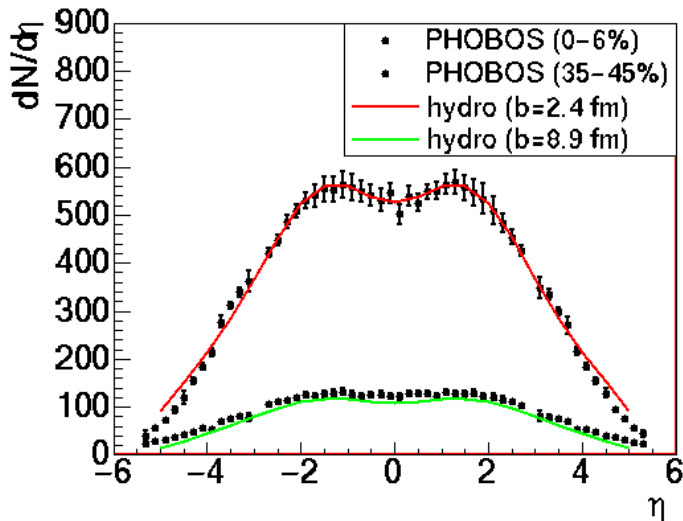
Jet quenching scenario is favored and initial state effect is ruled out.
But, this does not mean saturation model itself is killed.

Something happens only in AuAu collisions

Backup slides

Brief Summary of Our Hydro

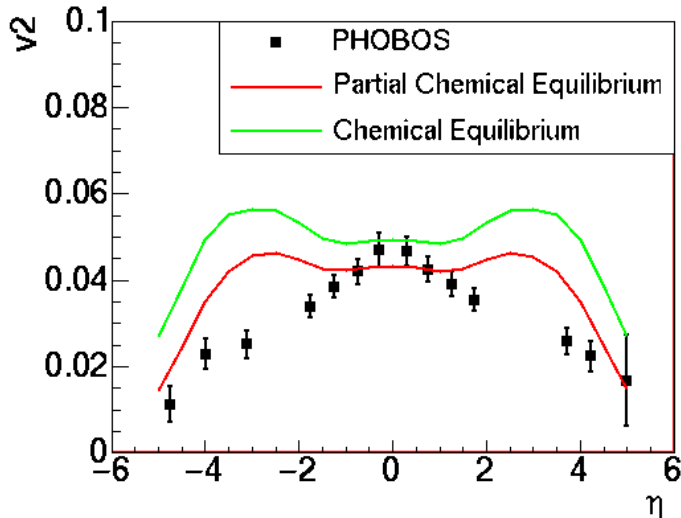
Results



- Full 3D hydro!

- ✧ No Bjorken scaling ansatz
- ✧ No cylindrical symmetry
- ✧ (τ, η_s, x, y) coordinate

T.Hirano, Phys.Rev.C65(2002)011901.

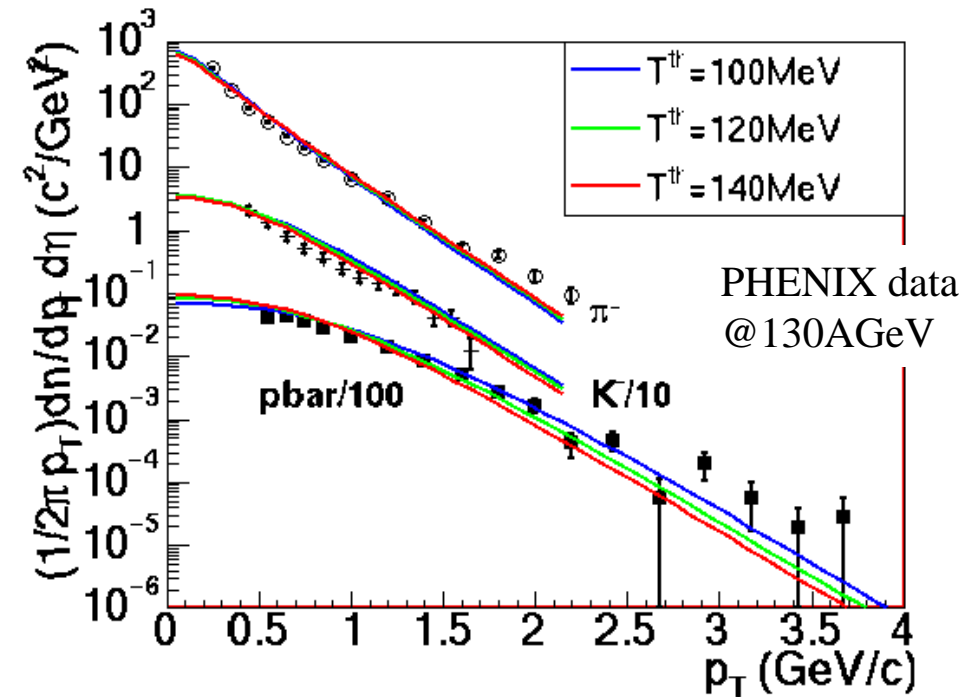


- $T^{\text{ch}} \neq T^{\text{th}}!$

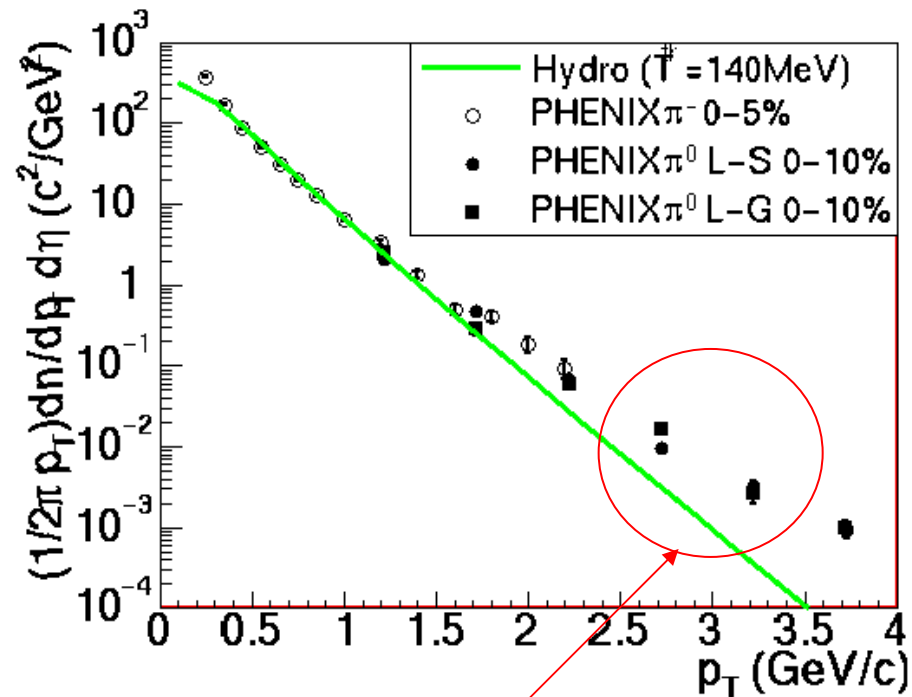
➤ Suppression of radial flow, elliptic flow and HBT radii in comparison with the conventional hydro results.

T.Hirano and K.Tsuda, Phys.Rev.C66(2002)054905.

Limit of Hydrodynamics @ High p_T

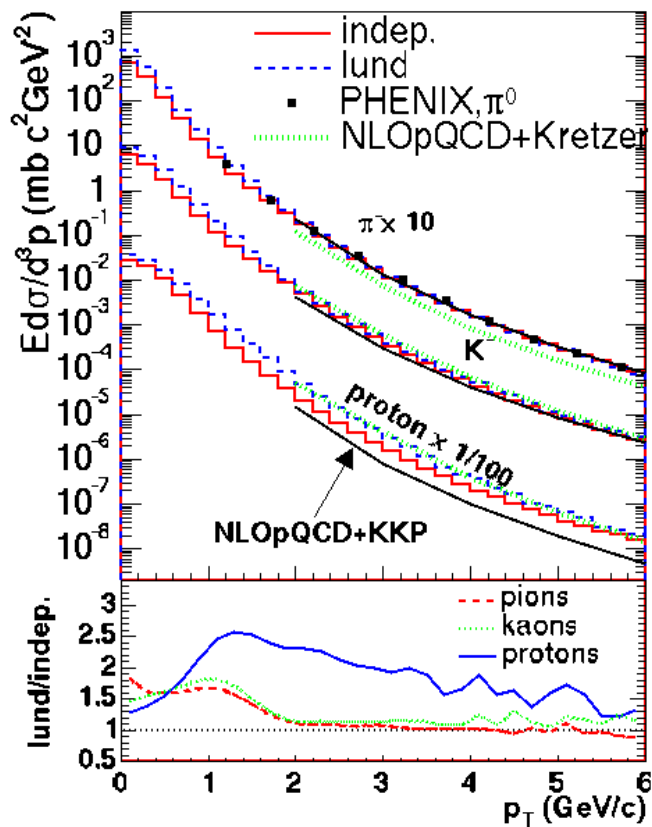


p_T slope for pions becomes insensitive to T^{th} in considering early chemical freezeout.



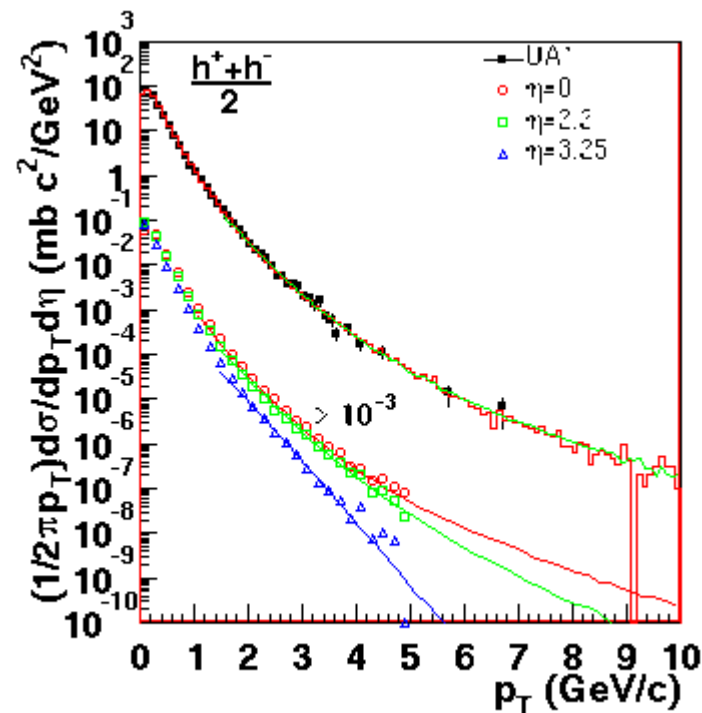
Need hard components?
 → Also one of the strong motivations of constructing the hydro+jet model

Results from PYTHIA



PHENIX π^0

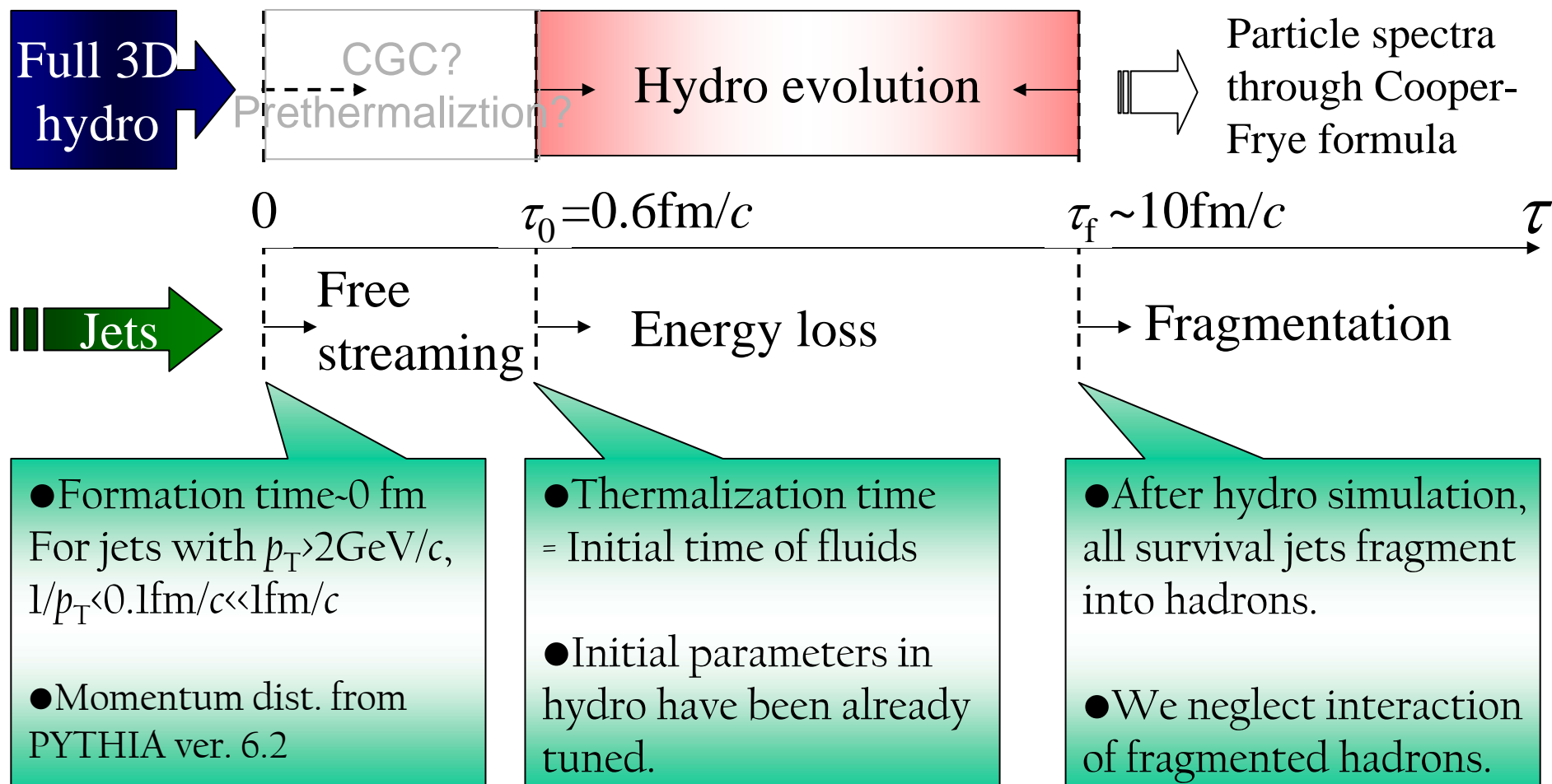
in pp collisions@200GeV,
hep-ex/0304038.



UA1 charged

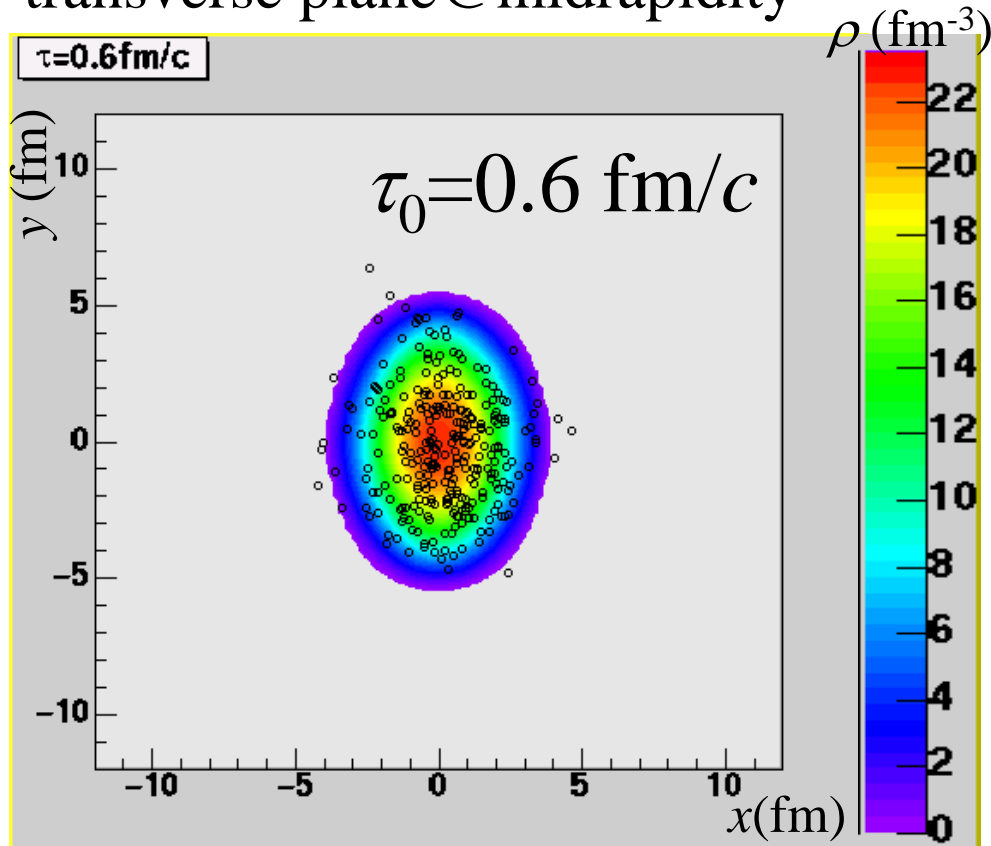
in $p\bar{p}$ collisions@200GeV,
Nucl.Phys.B335, 261(1990).

Time Evolution in Hydro+Jet Model



Initial Condition in the Transverse Plane

Au+Au 200A GeV, $b=8$ fm
transverse plane@midrapidity



Gradation

→ *Thermalized* parton density

Plot (open circles)

→ Mini-jets ($p_T > 2$ GeV/c)

• Initial configuration of mini-jets

→ Prop. to # of **binary collisions**

Parton Energy Loss

Relevant for
heavy-ion
collisions

Simplified GLV formula 1st order in opacity expansion

M.Gyulassy *et al.* (2000)

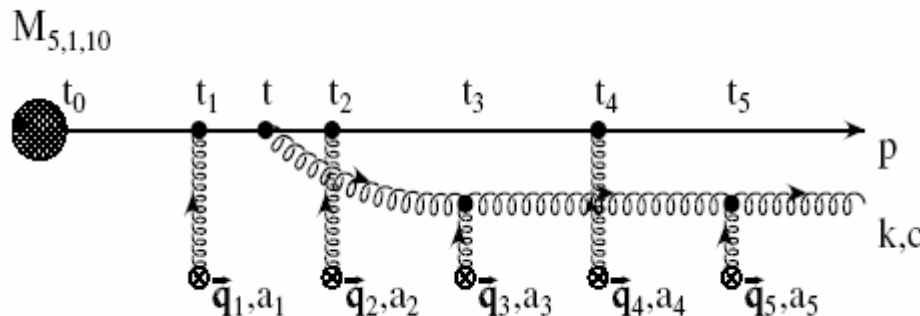
Initial
4-momentum
of a jet in local
rest frame

Position of a jet

$$\Delta E = -\frac{C}{\tau_0} \int_{\tau_0}^{\infty} d\tau (\tau - \tau_0) \rho(\tau, \mathbf{x}(\tau)) \ln \left(\frac{2p_0^\mu u_\mu}{\mu^2 L} \right)$$

Adjustable parameter

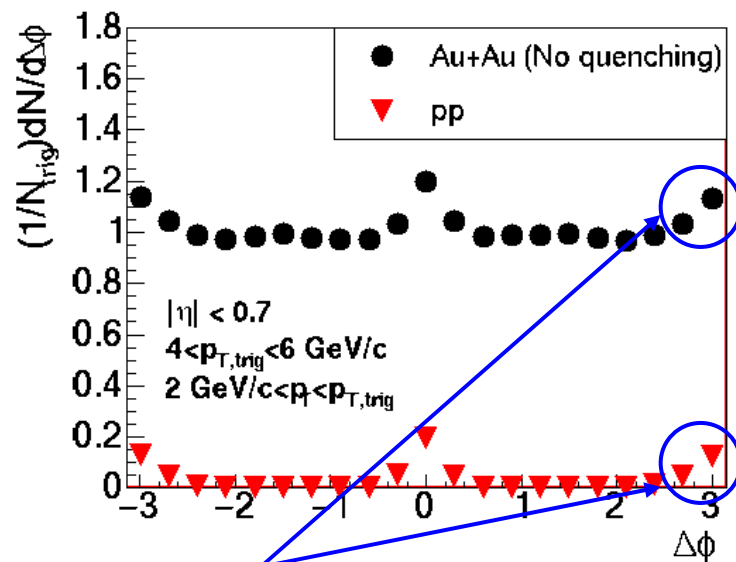
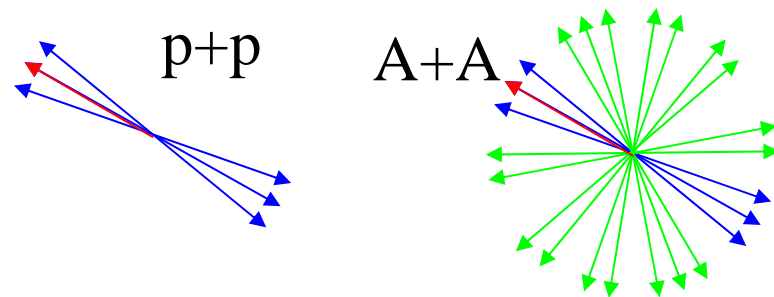
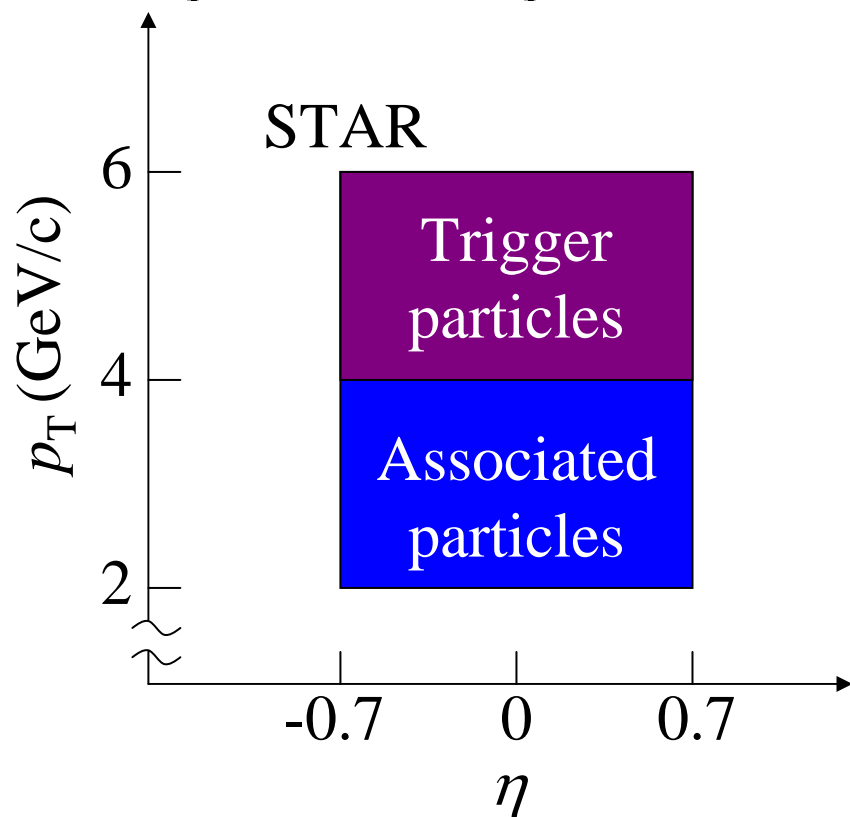
Parton density
from hydrodynamic
simulations
← We have already
had a solution!



Azimuthal Correlation Function

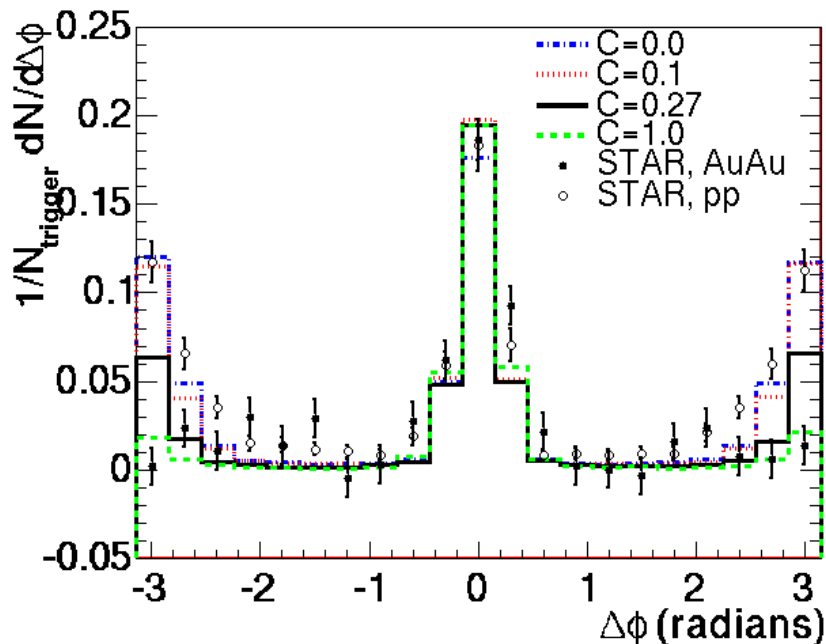
Back-to-back correlations of high p_T hadrons

$$\frac{1}{N_{\text{trig}}} \frac{dN}{d\Delta\phi} = \frac{1}{N_{\text{trig}}} \int d\Delta\eta \frac{dN}{d\Delta\phi d\Delta\eta}$$



Strength of away-side peaks are the same in **no** jet quenching case

1. Effect of Parton Energy Loss



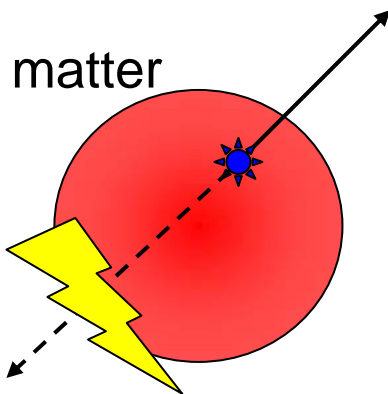
$$\frac{1}{N_{\text{trig}}} \frac{dN}{d\Delta\phi} = \frac{1}{N_{\text{trig}}} \int d\Delta\eta \frac{dN}{d\Delta\phi d\Delta\eta}$$

$C=0.27 \leftarrow$ From fitting R_{AA}

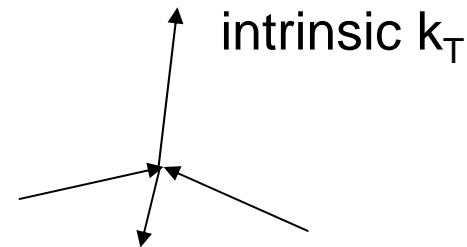
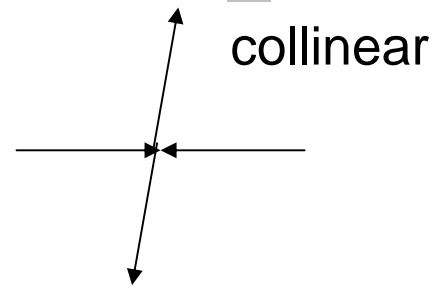
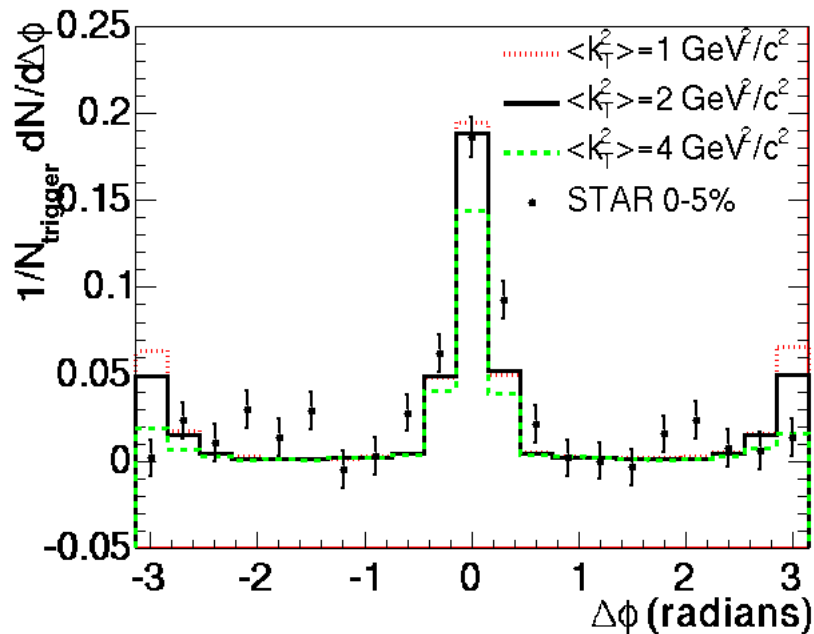
Simultaneous reproduction
of R_{AA} and C_2 ?

→ Another mechanism
is needed!

Hot matter



2. Effect of Intrinsic k_T

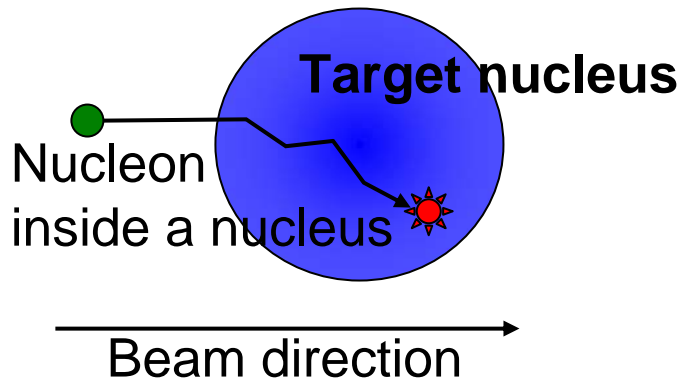


Primordial k_T distribution

$$g(k_T) \propto \exp(-k_T^2/\sigma_T^2)$$

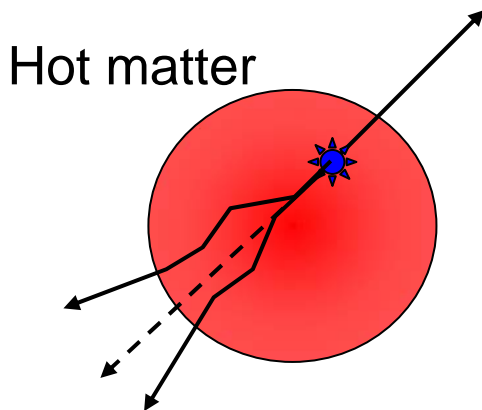
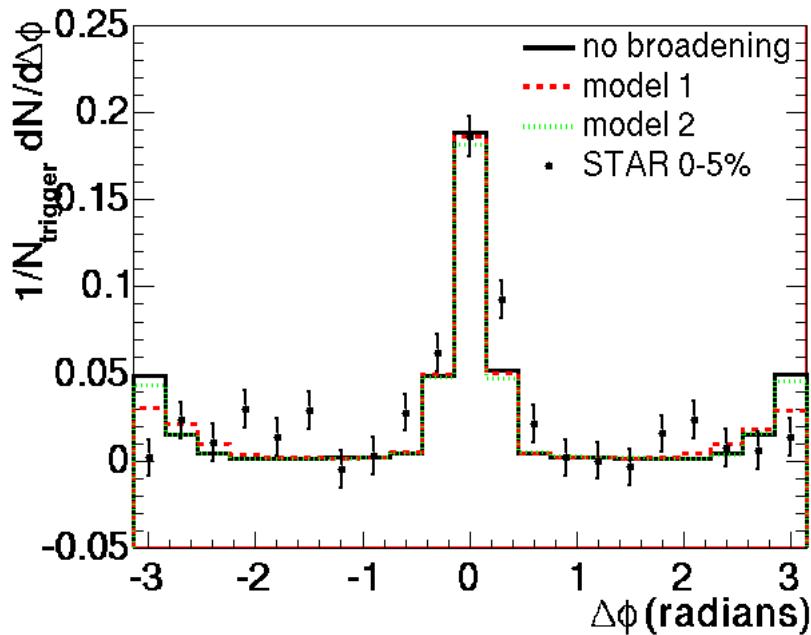
$$\langle k_T^2 \rangle = \sigma_T^2 = 1, 2 \text{ or } 4 \text{ GeV}^2/c^2$$

$$(\langle k_T^2 \rangle \sim 2 \text{ GeV}^2/c^2 @ \text{SPS})$$



Intrinsic k_T is **insufficient**
to the disappearance of
back-to-back correlation!

3. Effect of Broadening



p_{\perp} : Transverse momentum
orthogonal to its direction
of motion

Model 1 (BDMPS):

$$\langle p_{\perp}^2 \rangle = \frac{4}{\alpha_s N_c} \frac{dE}{dx}$$

$$\langle \langle p_{\perp}^2 \rangle \rangle = 2.5 \text{ GeV}^2/c^2$$

Model 2 (XNW):

$$\langle p_{\perp}^2 \rangle$$

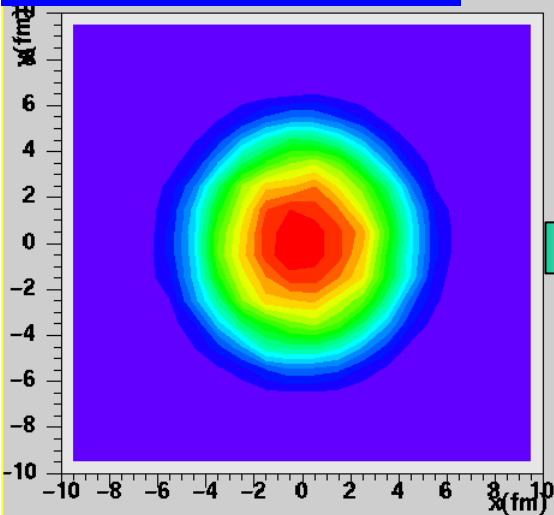
$$= (\alpha_s N_c / 2)^{-1} C \int \rho d\tau$$

$$\langle \langle p_{\perp}^2 \rangle \rangle = 0.78 \text{ GeV}^2/c^2$$

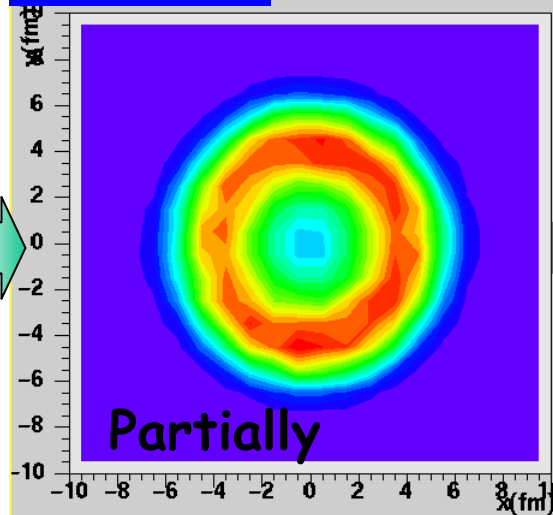
Surface Emission Dominance ?

Initial positions of jets which survive at final time

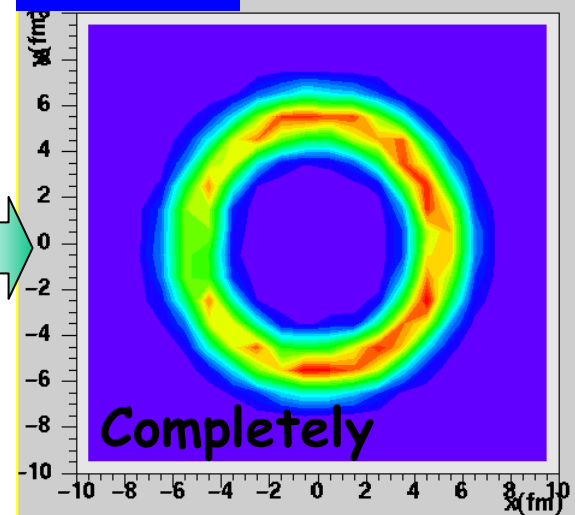
No quenching



$C=0.25$

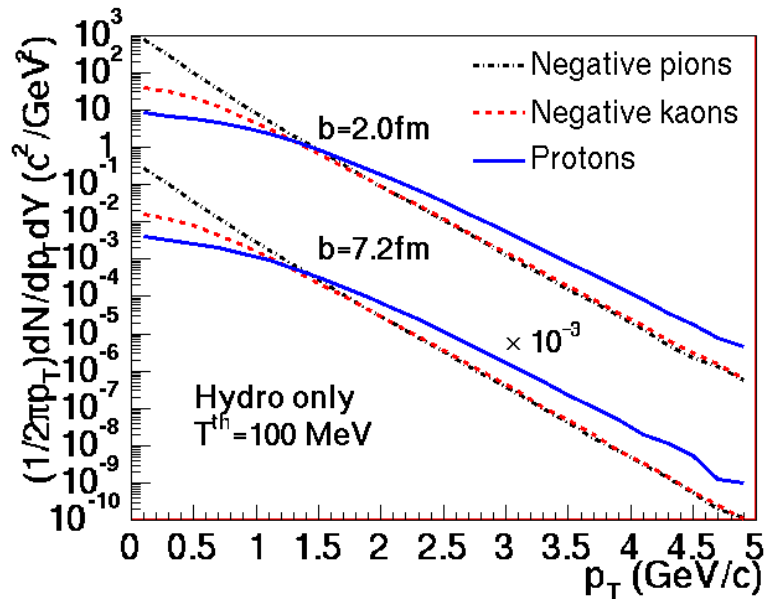


$C=1.0$

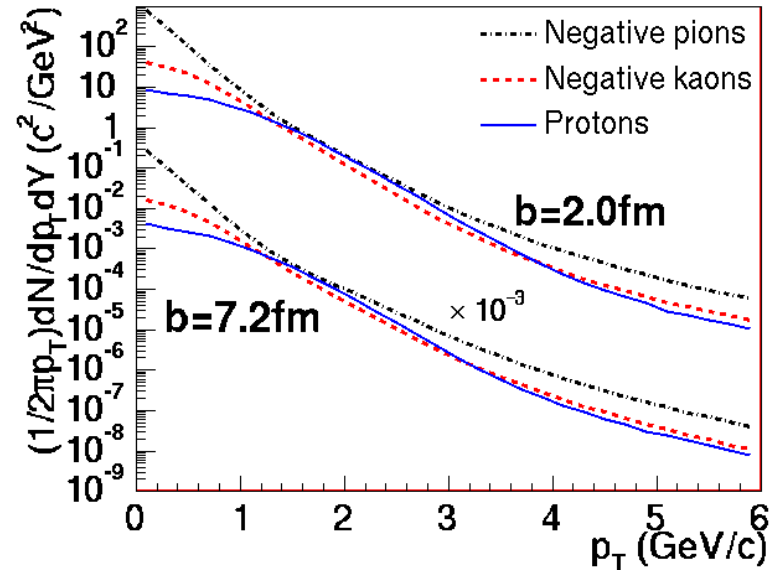


An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed. --J.D.Bjorken, FERMILAB-Pub-82/59-THY (1982).

Hydro and Hydrojet

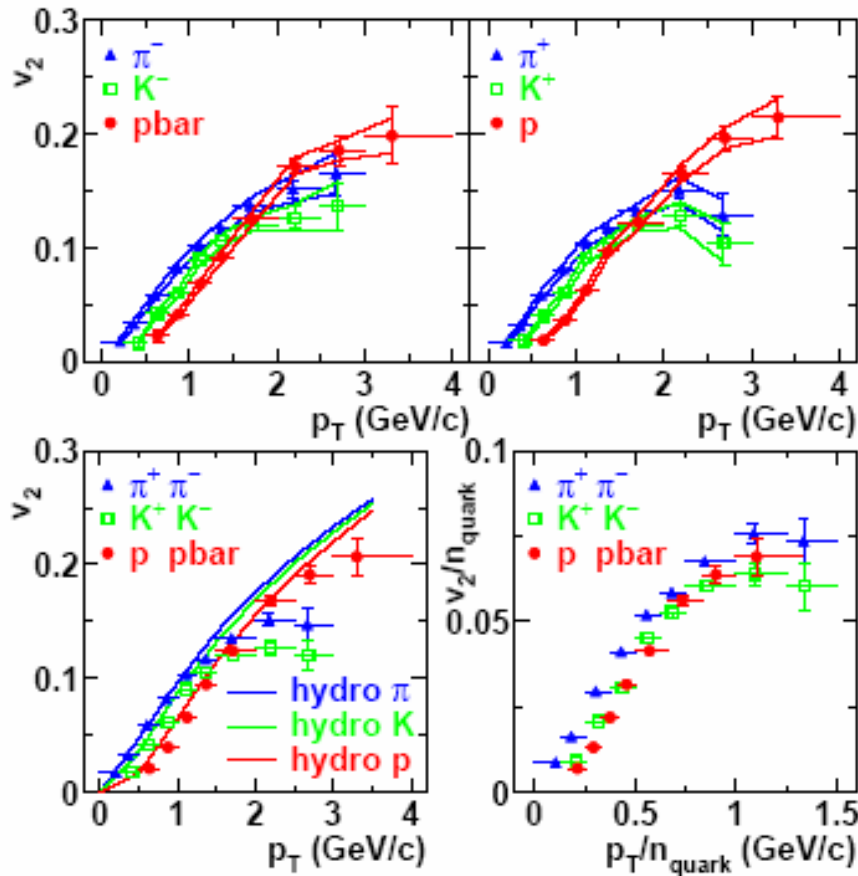


Radial flow pushes heavier particles to high p_T .



P_T spectrum becomes convex to concave.
 Inflection points at
 $\sim 2.8 \text{ GeV}/c$ (kaons)
 $\sim 3.5 \text{ GeV}/c$ (protons)

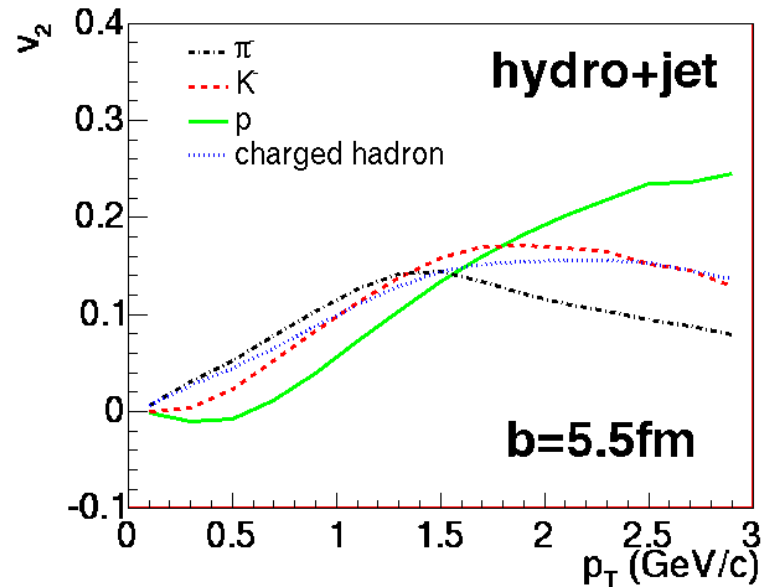
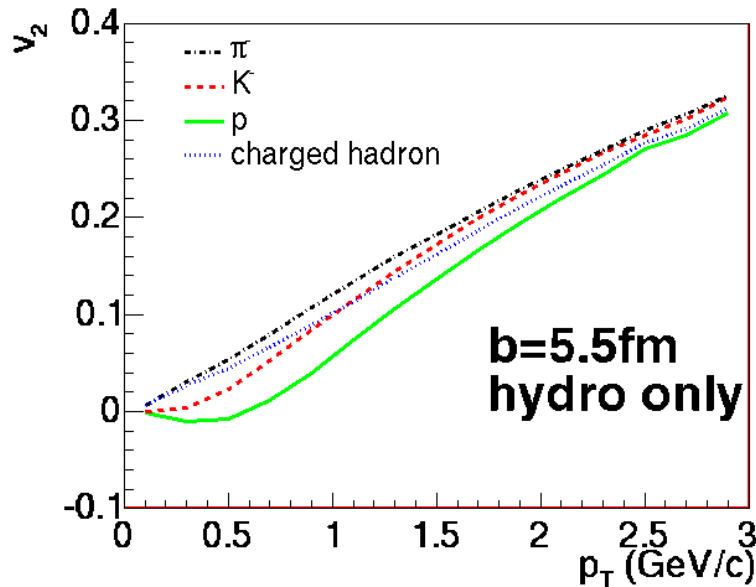
Elliptic Flow for Identified Hadron



$$v_2(p_T) = \frac{\int d\phi \cos(2\phi) \frac{dN}{dp_T d\phi}}{\int d\phi \frac{dN}{dp_T d\phi}}$$

$v_{2,p} > v_{2,\pi}$ hardly obtained
by using hydrodynamics.

Elliptic Flow for Identified Hadrons(cond.)



Hydro results:

Low p_T

→ Difference comes from mass

High p_T

→ All v_2 's merge ($p_T \gg m$)

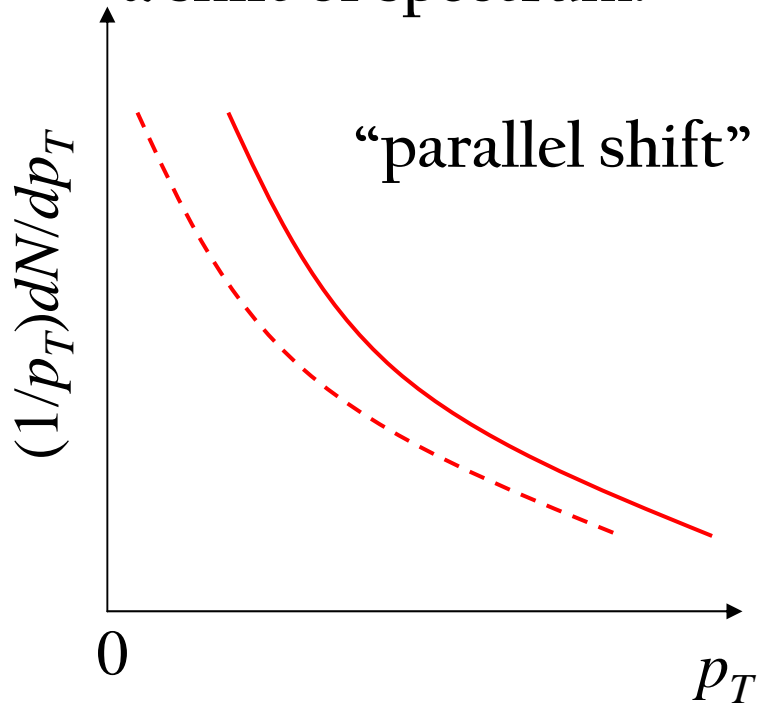
Interchanging behavior
of v_2 for id. hadrons

← Comes from hadron species
dependence of $p_{T,cross}$

$$v_{2,K} < v_{2,\pi} ???$$

Why $R_{AA}(\eta=0) > R_{AA}(\eta \sim 2)$?

Jet quenching is
a shift of spectrum.



R_{AA} is a ratio at a p_T

